The 1994 ICRP66 Human Respiratory Tract Dosimetry Model as a Tool for Predicting Lung Burdens from Exposures to Environmental Aerosols

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The International Commission on Radiological Protection's human respiratory tract dosimetry model was used to predict average particle deposition and retention patterns for two example trimodal (fine, intermodal, and coarse modes) environmental aerosols (Phoenix, Arizona, and Philadelphia, Pennsylvania). Deposited dose metrics are presented as mass (and number) of particles normalized to either respiratory tract region surface area (square centimeters) or mass (grams) of epithelium. Deposition metrics ranged over several orders of magnitude, with extrathoracic > tracheobronchial > alveolar–interstitial. Dissolution–absorption half-times for fine, intermodal, and coarse particles were defined as 10, 100, and 1000 days, respectively, to allow modeling of chronic exposures. Default values for particle physical clearance parameters were used. Retained dose for the alveolar–interstitial region is presented as the steady-state mass of particles (micrograms)/gram epithelium. Modeling results indicated similar retention patterns for the fine particles, but substantially different patterns for the intermodal and coarse particles. Intermodal and coarse particles dominated the Phoenix aerosol, resulting in predictions that long-term retained lung burdens would be about four times higher in individuals chronically exposed in Phoenix versus Philadelphia. This modeling approach improves the understanding of relationships between exposures to environmental aerosols and deposition/retention patterns in the human respiratory tract. Modeling demonstrated significant thoracic deposition of environmental aerosol particles larger than those collected in a $PM_{2.5}$ sampler. This result supports the conclusion that using the PM_{10} aerosol fraction as an exposure index should be a good indicator of potential health effects. Therefore, aerosol sampling should retain PM_{10} sampling in order to include the entire respirable size range and provide adequate information for predicting deposition and retained dose metrics for environmental aerosols. Ventilatory activity patterns are also necessary to characterize total personal exposure, and the dissolution–absorption of environmental aerosol particles must be determined to allow accurate modeling of their long-term retention in the lung. SNIPES, M.B.; JAMES, A.C.; JARABEK, A.M.: THE 1994 ICRP66 HUMAN RESPIRATORY TRACT DOSIMETRY MODEL AS A TOOL FOR PREDICTING LUNG BURDENS FROM EXPOSURES TO ENVIRONMENTAL AEROSOLS. APPL. OCCUP. ENVIRON. HYG. 12(8):547–554; 1997.

Humans are exposed to environmental aerosols that have a broad range of physical, chemical, morphological, and thermodynamic attributes. These aerosols contain a wide range of particle sizes and have naturally occurring constituents, as well as constituents produced by human technologies. Particle size is an important characteristic of aerosols because aerodynamic or thermodynamic properties markedly influence deposition patterns for inhaled particles. Particle composition is also important because many constituents of environmental aerosols exhibit toxicity to cells and tissues that could affect clearance mechanisms—thereby altering the residence time of retained particles—or influence other response mechanisms such as phagocytosis by alveolar macrophages. Composition also affects dissolution/absorptive rates, which influence the residence time and the response to particles retained in respiratory tract tissue, as well as remote tissues that are targets for absorbed constituents.

A growing epidemiological database indicates that exposures to environmental aerosols produce adverse biological responses.[1] Unfortunately, relationships among environmental aerosol concentrations, deposited doses of inhaled particles, and retention of inhaled environmental aerosol constituents are poorly understood. Characterizing the respiratory tract deposition and retention patterns in individuals exposed to environmental aerosols should improve the interpretation of exposure dose–response relationships that are needed for assessing epidemiological data to determine human health risks.

Selection of dose metrics for deposition and retention of particles for dose–response assessment should be based on insight into mechanisms of action for observed responses to deposited or retained particles. However, mechanistic insights into the health effects observed in the epidemiologic studies are only beginning to be elucidated for particulate matter.[1] At present, when considering epidemiologic data, effects can be categorized as acute and chronic. It is not known whether mass, surface area, or particle number is most appropriate for assessing potential toxicity. Further, questions remain about how the dose should be normalized (e.g., per ventilatory unit or critical cell type). Acute effects of particulate matter are probably best related to deposited particle burdens of short duration, whereas a steady-state retained burden may be most appropriate to characterize chronic responses.

Models are useful for predicting deposition and accumulation patterns of inhaled materials. To date, however, no model

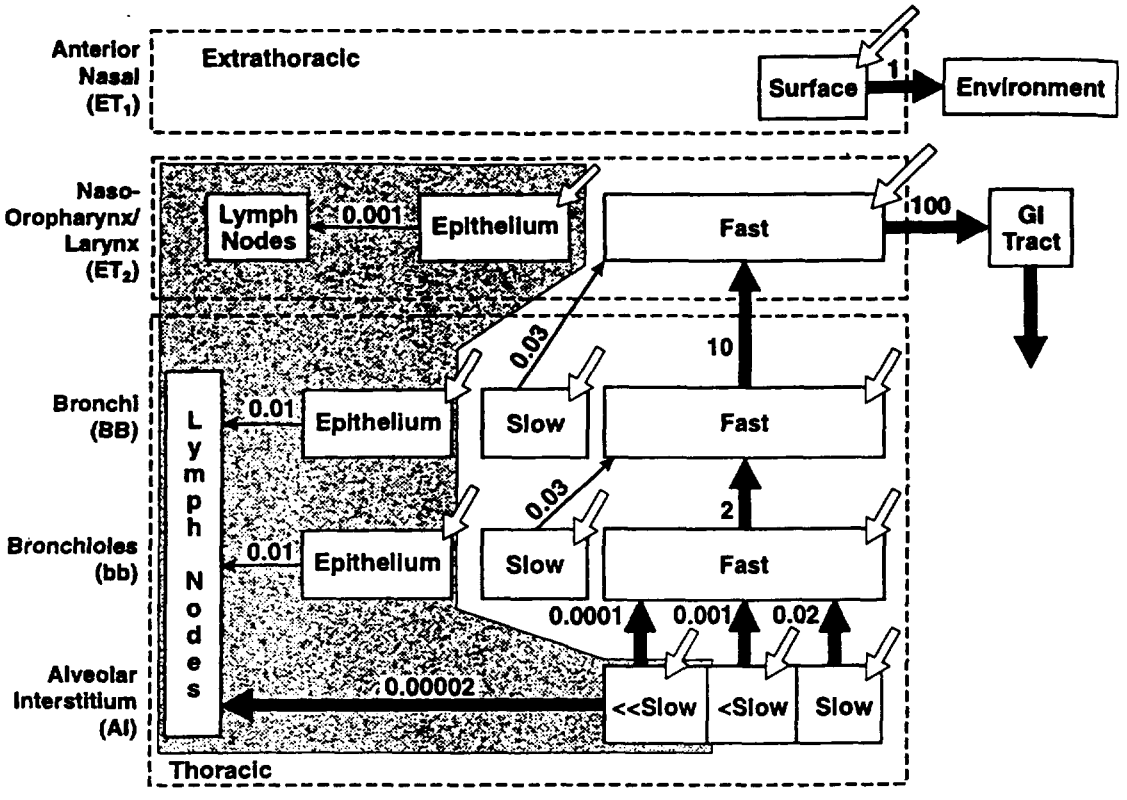

FIGURE 1. Schematic of the ICRP66 human respiratory tract dosimetry model.[1] Open arrows show regions into which inhaled particles can deposit. Solid arrows represent time-dependent particle transport pathways from each region. Particles that deposit in the thoracic region physically clear at slow or fast rates by mucociliary action in BB and bb, and by macrophage-mediated transport in the AI region; the default ICRP particle transport rate constants are shown beside the solid arrows and have units of d^{-1}. Stippling indicates the compartments with clearance pathways sequestered in tissue rather than associated by surface transport. ET_1 = anterior nose; ET_2 = posterior nasal passages, larynx, pharynx, and mouth; BB = bronchial region; bb = bronchiolar region (bronchioles and terminal bronchioles); AI = alveolar–interstitial region (respiratory bronchioles, alveolar ducts and sacs with their alveoli, and interstitial connective tissue).

specific for predicting these patterns in the human respiratory tract has been developed for repeated inhalation of environmental aerosols. The revised International Commission on Radiological Protection (ICRP) human respiratory tract dosimetry model for radiological protection[2] was developed to predict radiation dose rates and cumulative radiation doses from acute or chronic inhalation exposures of humans to radioactive aerosols. Figure 1 is a schematic of the ICRP66 model. Compartments of the model with clearance pathways are shown; details of the model structure and rates associated with the pathways are discussed elsewhere.[2] The ICRP66 model was used in this article to demonstrate respiratory tract deposition and accumulation patterns for selected environmental aerosols. Model limitations and needs relevant to understanding relationships between inhalation exposures to environmental aerosols and the consequent deposition and accumulation patterns of constituents of environmental aerosols are discussed.

Methods

The ICRP66 model was developed for use in radiological protection and is structured to predict absorbed radiation doses resulting from inhalation of radioactive aerosols. The particle deposition component of the model applies equally well to radioactive or nonradioactive particles. Providing that the particles are not highly charged, the only particle factors influencing deposition are their physical size, shape, density, and hygroscopicity, all of which are addressed by the ICRP deposition model. The deposition data used to develop the model were from human radioactive tracer studies in which accurate measurements were obtained using very low particulate mass burdens of innocuous (chemically and radiologically nontoxic) materials. The small respiratory tract burdens precluded the possibility of experimental artifact due to lung overload phenomena. Assuming that exposures to environmental aerosols are sufficiently low in terms of deposited particle mass or toxicity so as not to cause altered rates of lung clearance, and that the dissolution–absorption rates of the deposited particles are known (or can be estimated) as a function of time, the reference clearance rates defined for the ICRP clearance model can also be used to predict the buildup and retention of particle number, mass, or surface area in the alveolar–interstitial (AI) region, as a function of time, for a given pattern of chronic exposure. The only difference in application of the model to nonradioactive versus radioactive particles is that the reduction in the amount of material retained that is caused by radioactive decay does not have to be factored into the calculation for nonradioactive particles. Soft-

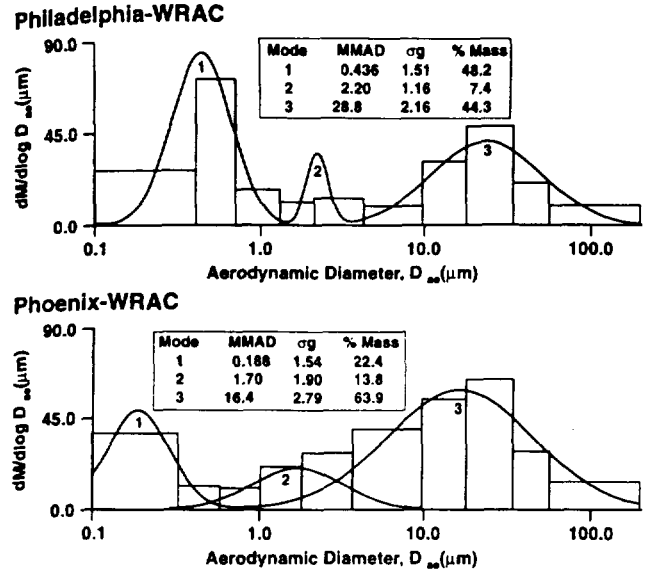

FIGURE 2. Example environmental aerosols for two U.S. cities. The aerosols were collected using a wide range aerosol classifier (WRAC) (modified from Reference 3).

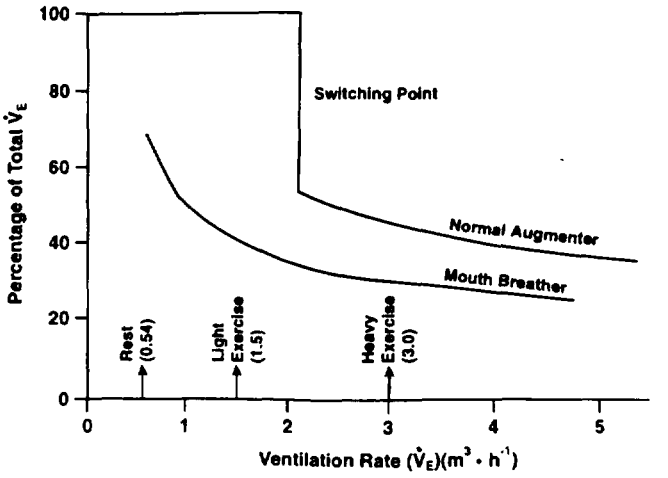

FIGURE 3. Percentage of total ventilation (V_E) passing through the nasal route of human normal augmenters (solid curve) and habitual mouth breathers (broken curve). Reprinted with permission from *Annals of the ICRP* (Volume 24, Nos 1–3, 1994; ICRP Publication 66; Page 238).

ware developed for use with the ICRP66 model (LUDEP®, version 1.1; National Radiological Protection Board, 1994) was used to perform the simulations described in this article.

For this application, the ICRP66 model was simplified for ease of presentation and to provide a level of detail approximately commensurate with the observed effects reported in epidemiological studies. The two extrathoracic (ET) compartments (ET_1 and ET_2) were combined and defined as the ET region; the two tracheobronchial (TB) compartments (BB and bb) were combined and defined as the TB region. The AI region defined in the ICRP66 model was not changed.

Deposition for the ET, TB, and AI regions and retention patterns for the AI region were modeled for environmental aerosols (Figure 2) that were characterized for Philadelphia, Pennsylvania, and Phoenix, Arizona.[3] These environmental aerosols were chosen to represent a comparison between eastern and western U.S. cities. The size distributions of the aerosols from both cities were described as trimodal (fine, intermodal, and coarse modes). It is not known at this time whether the intermodal mode is real or an artifact of sampling procedures.[1] The distribution of mass, particle numbers, and particle surface area for the Philadelphia and Phoenix aerosols are indicated in Table 1.

Air concentrations for both environmental aerosols were assumed to be 50 $\mu g/m^3$, and inhalation of the aerosols was considered continuous for 24 hours/day, 7 days/week. Deposition rates (micrograms/day) were modeled for normal augmenters and adult male mouth breathers. Normal augmenters are individuals who normally breathe through their noses, but who involuntarily switch to a combination of nose and mouth breathing as the ventilation rate increases (Figure 3). This change in breathing pattern occurs at a ventilation rate of about 2.1 m^3/hour, at which time about 60 percent of the minute ventilation is through the nose and about 40 percent is through the mouth. At a ventilation rate of 5 m^3/hour, about 60 percent of the air is inhaled and exhaled through the mouth and 40 percent through the nose. Note that mouth breathers inhale and exhale about 70 percent through the nose at rest and about 30 percent through the nose at a breathing rate of about 5 m^3/hour. There is always a flow of at least 30 to 40 percent of inspired and expired air through the nose, with heavy exercise dictating that 60 to 70 percent of this inspired and expired air will flow through the mouth.

TABLE 1. Percent of the Total Mass, Particle Number, or Surface Area of Each of the Three Modes for Philadelphia and Phoenix Aerosols

Aerosol Mode	Philadelphia			Phoenix		
	Mass	Number	Surface	Mass	Number	Surface
Fine	48.2	99.946	95.4	22.4	99.6	85.5
Intermodal	7.4	0.050	2.5	13.8	0.3	7.4
Coarse	44.3	0.004	2.1	63.9	0.1	7.1

Three different ventilation activity patterns were used for modeling deposition, corresponding to the general population, light workers, and heavy workers. The patterns represent different amounts of time spent per day at different levels of exertion and therefore ventilation (Table 2). Whereas particle size and distribution are key input parameters governing deposition of inhaled particles and represent key attributes of the ambient aerosols, ventilatory activity pattern is the major physiologic parameter.

For this modeling effort, daily average deposited particle mass and number burdens normalized to either regional respiratory tract surface area (square centimeters) or mass (grams) of epithelium in each region were chosen as dose metrics to characterize acute exposures. Because chronic effects of particles are probably best attributed to particle burdens or damage over many years, steady-state average particle retention was modeled only in the AI region, where clearance processes occur over weeks to years. Particle burdens in the AI region

TABLE 2. Human Activity Patterns and Associated Respiratory Minute Ventilation

Activity Pattern	Sleeping (0.45 m^3/hour)		Sitting (0.54 m^3/hour)		Light Activity (1.5 m^3/hour)		Heavy Activity (3.0 m^3/hour)		Total/Day	
	Hours	Total m^3	Hours	Total m^3	Hours	Total m^3	Hours	Total m^3	Hours	Total m^3
Adult male, general population	8	3.6	8	4.32	8	12	0	0	24	19.9
Adult male, light work	8	3.6	6.5	3.5	8.5	12.75	1	3	24	22.85
Adult male, heavy work	8	3.6	4	2.16	10	15	2	6	24	26.76

From the ICRP.[2]

resulting from chronic exposures to the two example environmental aerosols were modeled for the normal augmenter from the general population. Model results for average retained particle burdens in the AI region were normalized to the mass of AI tissue and presented as specific AI tissue burden (micrograms particles/gram AI tissue) as a function of time.

A very important input parameter to model chronic inhalation exposures was the dissolution–absorption half-time of the deposited particles. The ICRP66 model accounts for clearance from the respiratory tract as a result of dissolution of particles or elution of their constituents, followed by absorption of the dissolved constituents into cells proximate to the particles, or into the circulatory system for redistribution or excretion. Information about the dissolution–absorption rates for particles in these environmental aerosols is not available. Rates for dissolution–absorption were assumed on the basis of particle size and probable chemical attributes of the three aerosol modes. The dissolution–absorption half-times for the fine, intermodal, and coarse aerosol modes were assumed to be 10, 100, and 1000 days, respectively, for both example aerosols. Another important variable for modeling chronic inhalation exposures to the AI region of the respiratory tract is the physical clearance rate for deposited particles. Default values recommended in the ICRP66 model were used as physical clearance rates of these aerosol particles. Table 3 summarizes the assumptions used to model chronic exposures of adult male normal augmenters to these two trimodal environmental aerosols.

Results

Predicted daily average mass deposition (micrograms/day) in the TB and AI regions as a function of particle size for an exposure concentration of 50 $\mu g/m^3$ is presented in Figure 4 for the Philadelphia environmental aerosol and in Figure 5 for the Phoenix aerosol. Predictions are given for adult male normal augmenters versus mouth breathers and activity patterns for the general population, light workers, and heavy workers. When compared with normal augmentation, larger amounts of particles can penetrate to the TB or AI regions with mouth breathing because of the lower filtration efficiency of the mouth. Penetration to the lower respiratory tract is especially enhanced for the larger particles [≥ 2 μm mean mass aerodynamic diameter (MMAD)], which normally deposit preferentially in the ET region as a result of impaction. For heavy workers, in which about 70 percent of the ventilation is through the mouth (Figure 3), deposition of particles <2 μm in diameter is almost independent of mode of breathing because the small particles deposit by sedimentation and diffusion. The differences between the regional deposition patterns for the Philadelphia and Phoenix aerosols are due to the fact that the mass of particles was about equally split between the fine and coarse modes of the Philadelphia aerosol, whereas three-quarters of the mass of the Phoenix aerosol was particles >1 μm and one-quarter was <1 μm.

Table 4 presents the predicted average daily mass deposition fraction of the example environmental aerosols as nanograms particles/square centimeter/day for the ET, TB, and AI regions of a normal augmenter from the general population. The relative masses of particles per square centimeter reflect the large differences in surface area (see footnote to Table 4) for the three regions. Substantially more mass is deposited per square centimeter of the ET region than in the TB or AI regions.

TABLE 3. *Model Calculated Particle Deposition Input Parameter Values* Used to Predict Average Particle Mass Retention in the AI Region of the Respiratory Tract of an Adult Male Normal Augmenter with a General Population Activity Pattern for Chronic Exposures (24 Hours/Day, 7 Days/Week) to Environmental Aerosols Containing 50 μg Particles/m^3

- Model calculated average daily particle deposition (micrograms) in the AI region. These deposition values were derived using the MMAD, σ_g, and percent mass values indicated in Figure 2.

	Fine	Intermodal	Coarse	Total
Philadelphia	37.1	11.3	1.2	49.6
Phoenix	26.5	17.2	11.9	55.6

- Dissolution–absorption half-times for aerosol modes assumed to be:
  - fine = 10 days;
  - intermodal = 100 days; and
  - coarse = 1000 days.
- Default ICRP66 values for particle physical clearance parameters (see Figure 1 and References 1 and 2 for a description of the default values and their sources).

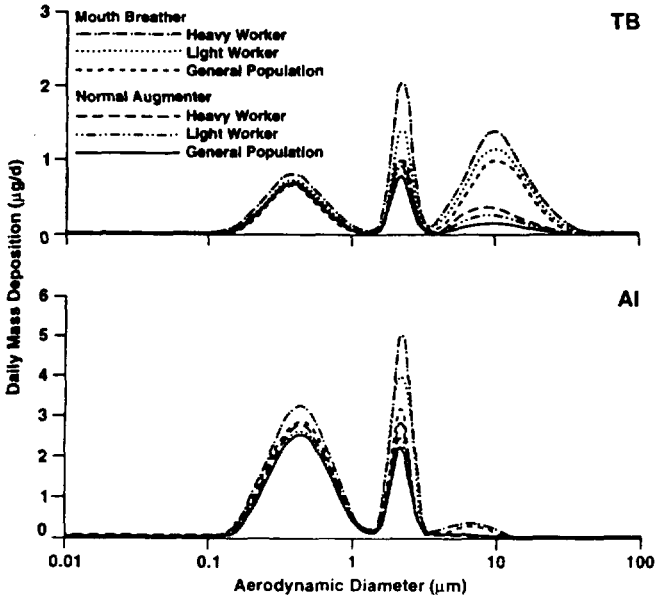

FIGURE 4. Predicted average daily mass deposition (micrograms/day) as a function of MMAD for the Philadelphia environmental aerosol inhaled at a concentration of 50 $\mu g/m^3$.

However, particles that are deposited in the ET region clear rapidly via the mucociliary pathway. Likewise, substantially more mass deposits per square centimeter on the surface of the TB region than the AI region, but most of the particles that are deposited in the TB region are also believed to be cleared quickly. Table 5 presents the predicted daily deposition per gram of target tissue (nanograms particles/gram/day) for the ET epithelium, the TB epithelium, and the AI tissue.[1] Data in

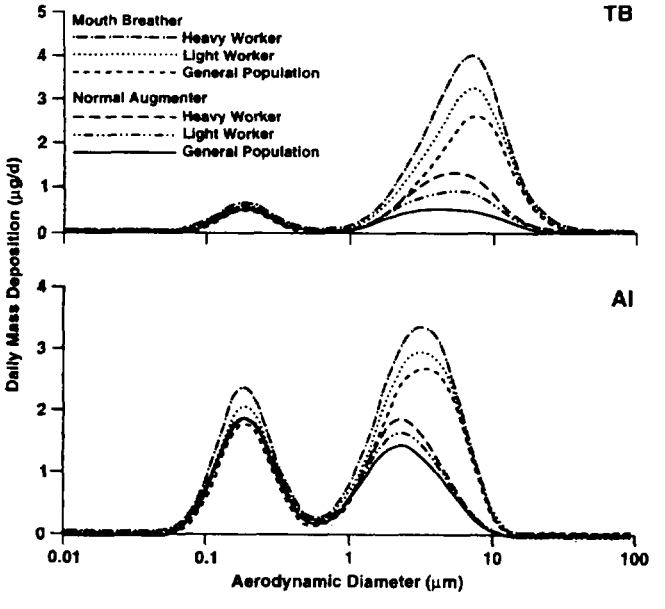

FIGURE 5. Predicted average daily mass deposition (micrograms/day) as a function of MMAD for the Phoenix environmental aerosol inhaled at a concentration of 50 $\mu g/m^3$.

TABLE 4. Predicted Daily Mass of Particles Deposited Per Unit of Tissue Surface Area in a Normal Augmenter for Example Environmental Aerosols Inhaled for 24 Hours/Day, 7 Days/Week at a Concentration of 50 $\mu g/m^3$

	Philadelphia			Phoenix		
Region*	Fine	Inter-modal	Coarse	Fine	Inter-modal	Coarse
ET	81	96	560	16	140	890
TB	3.2	1.3	0.9	3.0	1.8	3.5
AI	0.025	0.0077	0.00078	0.018	0.012	0.0081

Values are nanograms particles/square centimeter/day.
*Surface area of ET epithelium = 470 cm^2; TB epithelium = 2690 cm^2; AI epithelium = 1.475×10^6 cm^2 (from Reference 2, Table 1).

Tables 4 and 5 demonstrate that there are large differences in initial deposition metrics for the ET, TB, and AI regions when deposition is expressed as mass of particles either per surface area or per mass of epithelial tissue. It is noteworthy that a substantial mass of particles from the coarse aerosol modes is deposited on the TB epithelium, and this deposition should not be ignored, especially if a portion of the deposited particle burden is cleared slowly.[5]

Figure 6 shows predicted daily average particle number deposition normalized to respiratory tract surface area as a function of particle size. When average deposition is expressed as numbers of particles/square centimeter/day, regional concentrations of deposited particles are different by one to four orders of magnitude, with ET > TB > AI. Particle numbers in these two environmental aerosols are dominated by the fine aerosol modes, so numbers of particles deposited/square centimeter in the ET, TB, and AI regions were predicted to be higher for particles <1 μm. However, about equal numbers of particles/square centimeter are predicted to deposit in each respective region of the respiratory tract for the very small particles and particles of about 1 to 5 μm.

The modeling results for predicted average AI time-dependent burdens of particles resulting from chronic exposures to the two environmental aerosols at a concentration of 50 $\mu g/m^3$ are presented in Figure 7. Equilibrium between deposition and clearance was predicted to occur after about 70, 700, and 7000 days, respectively, for the fine, intermodal, and coarse aerosol modes. The same total mass of aerosol particles

TABLE 5. Predicted Daily Mass of Particles Deposited Per Unit of Tissue Mass in a Normal Augmenter for Example Environmental Aerosols Inhaled for 24 Hours/Day, 7 Days/Week at a Concentration of 50 $\mu g/m^3$

	Philadelphia			Phoenix		
Region*	Fine	Inter-modal	Coarse	Fine	Inter-modal	Coarse
ET	16,000	19,000	110,000	3200	28,000	180,000
TB	1700	670	470	1500	920	1800
AI	34	10	1	24	16	11

Values are nanograms particles/gram tissue/day.
*Mass of ET epithelium = 2.4 g, calculated from surface area of 470 cm^2 × average thickness of 50 μm; TB epithelium = 5.2 g, calculated from surface area of 290 cm^2 for the BB epithelium × average thickness of 15 μm, plus surface area of 2400 cm^2 × average thickness of 15 μm; AI epithelium = 1100 g (Reference 2, Figures 5 and 6; Table 1).

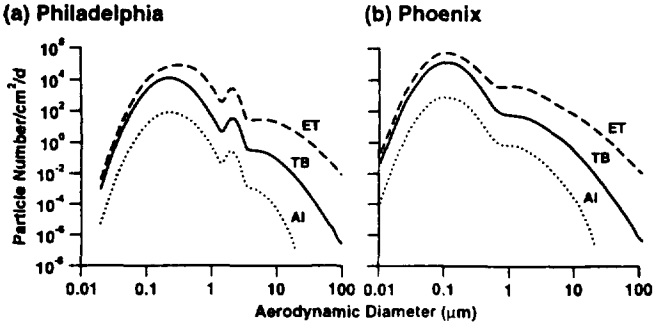

FIGURE 6. Predicted average daily particle number deposition per unit of surface area (particles/square centimeter/day) in a normal augmenter from the general population as a function of MMAD for the Philadelphia and Phoenix environmental aerosols inhaled at a concentration of 50 $\mu g/m^3$.

was predicted to deposit per day in the AI region for both aerosols (Table 3). However, 1.5 times as much intermodal and 10 times as much coarse-mode Phoenix aerosol were deposited per day as compared with the Philadelphia aerosol. More particle mass occurred in the coarse mode for the Phoenix aerosol, and a dissolution–absorption half-time of 1000 days was assumed in modeling the clearance of the coarse-mode particles. Therefore, a higher equilibrium lung burden was predicted for the Phoenix aerosol than for the Philadelphia aerosol. Overall, individuals exposed for long periods to the Phoenix aerosol are predicted to have almost four times as much total dust in their lungs as individuals exposed to the Philadelphia aerosol, primarily because of the difference in the amount of coarse aerosol mode for these two environmental aerosols.

For chronic inhalation exposures to the Phoenix or Philadelphia environmental aerosols, assuming relatively constant physical and chemical attributes over time, equilibrium amounts of dust are predicted to be achieved after about 18 years. The steady-state retained mass burdens of particles would be composed mainly of particles from the coarse aerosol mode, and the specific lung burden would remain constant as long as exposure conditions remained relatively constant.

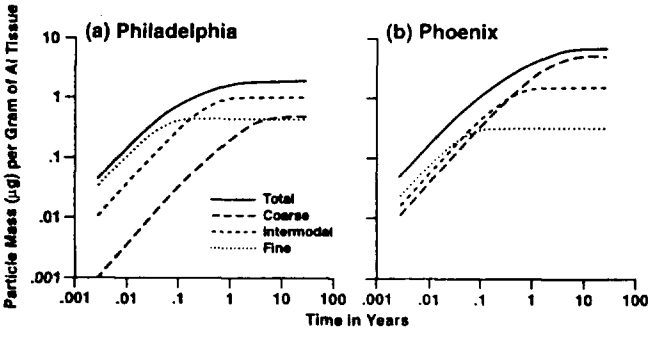

FIGURE 7. Average specific burdens of particles (micrograms particles/gram AI tissue) predicted for a normal augmenter from the general population exposed 24 hours/day, 7 days/week to Philadelphia or Phoenix environmental aerosols containing 50 μg particles/m^3.

Discussion

The revised ICRP human respiratory tract dosimetry model was used to evaluate average daily deposition patterns in the ET, TB, and AI regions of the respiratory tract for example environmental aerosols characterized for Philadelphia, Pennsylvania, and Phoenix, Arizona. Model results indicate substantial differences between these environmental aerosols in deposition and retention metrics for the coarse-mode particles. Such differences in deposition suggest that differences should be noted in biological responses to these aerosols if the coarse-mode particles cause the responses.

The fine particle modes of these environmental aerosols contain more than 99 percent of the number distribution of particles. Because fine aerosol particles are deposited primarily by sedimentation and diffusion, they can penetrate deeply into the respiratory tract. Therefore, fine particles contribute a large fraction of the average thoracic deposition. The deposition metrics were similar for the fine modes of the two aerosols, which suggests that any differences in biological responses should be associated with differences in chemical constituents and/or surface area of the fine-mode particles if they are responsible for biological responses.

Examination of alternative deposition metrics yields interesting information about deposition versus particle size in the TB and AI regions. For example, large numbers of all particle sizes are deposited per square centimeter (or per gram) of epithelium in the TB region. These deposition metrics for the TB region are two orders of magnitude larger than the same metrics for the AI region. Model results for numbers of particles deposited either per square centimeter or per gram of TB epithelium suggest that all particle sizes in these environmental aerosols should be evaluated in terms of their potential importance to biological responses to inhaled environmental aerosols.

Particle mass from the coarse mode of environmental aerosols dominates long-term retention and cannot be excluded from evaluations of biological effects of environmental aerosols. This is an important consideration when directed toward regulating ambient aerosols with samples of size cut-points other than PM_{10} (for example, $PM_{2.5}$). The PM_{10} samplers collect a range of particle sizes that approximates particles that are deposited in the human thorax (i.e., TB and AI regions) during inhalation exposures, even if breathing is via the mouth (Figure 8). A $PM_{2.5}$ sampler adequately collects fine particles of the environmental aerosol, but excludes a portion of the coarse aerosol mode particles that potentially could deposit in the respiratory tract. This modeling effort indicates that significant deposition of particles larger than the cut-point of a $PM_{2.5}$ sampler occurs and supports the use of the PM_{10} fraction as an exposure index of particles with the potential for thoracic deposition and retention. There is no clear dosimetric motivation for the use of a $PM_{2.5}$ fraction in relation to deposited or retained particle mass. However, a rationale for a fine particle standard could be based on consideration of differences in composition and potential toxicity of the fine versus coarse modes.[1]

Adequate information on key input parameters is an important factor in using the ICRP66 human respiratory tract dosimetry model, or any other model, to predict the consequences of exposures to environmental aerosols. Breathing

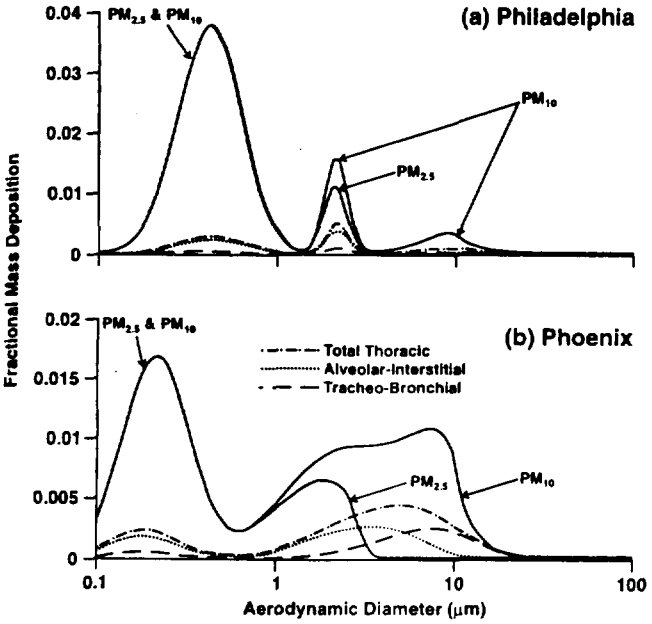

FIGURE 8. Predicted mass deposition fractions in lower respiratory tract regions and mass fractions collected by a PM_{10} or $PM_{2.5}$ sampler versus MMAD for an exposure to either Philadelphia (a) or Phoenix (b) aerosol at a concentration of 50 $\mu g/m^3$. Predictions are shown for an adult male mouth breather with a general population activity level.

mode (normal augmentation versus mouth breathing) and ventilatory activity pattern were shown to be key determinants of initial deposition. Also, the predicted deposition and retention patterns represent averages. Local doses can be influenced by local ventilatory patterns in the thorax, but adequate information is not available to assess the degree of nonuniformity of particle deposition and retention resulting from differences in local ventilation patterns. Average dose predictions probably underestimate actual doses to specific local areas in the respiratory tract where deposition is enhanced by air flow patterns or by nonuniform clearance. Anatomical data are needed to support models that can be used to compute local versus average doses, especially across gender, age, and disease states (e.g., chronic obstructive pulmonary disease). Additionally, aerosol flow patterns during inspiration and expiration can influence particle deposition patterns. Air sampling strategies should collect data on microenvironment exposure concentrations that correspond to associated activities and representative ventilatory levels, so that inhaled dose construction efforts can take advantage of dosimetry models that account for inhalation dynamics. The use of representative ventilatory patterns as input will ensure more accurate characterization of total personal human inhaled dose.

Physical attributes (i.e., particle size and distribution) and other physicochemical factors (e.g., composition and hygroscopicity) are also important. These factors are relatively easy to quantify, and their routine reporting would aid dosimetry modeling efforts. With respect to constructing accurate retained dose metrics for particles in the respiratory tract, *in vivo* dissolution–absorption rate characteristics are key determinants of particle clearance. These characteristics are more difficult to determine and were not done for the different modes of the Philadelphia and Phoenix aerosols. The approximations for dissolution–absorption rates used in this article could therefore yield only illustrative modeling results that would be improved with accurate values for these parameters.

Conclusions

The ICRP human respiratory tract model can be used to help evaluate deposition of environmental aerosol particles in all regions of the respiratory tract. Various deposition metrics can be selected, including average mass or number of particles per unit of area or mass of the target tissues. The model can also be used to simulate chronic inhalation exposures that result in long-term, retained constituents of environmental aerosols.

Substantial amounts of environmental aerosols are deposited in the TB region. While clearance is rapid for most of the deposited particles, some fraction of the deposited particles remains associated with the TB epithelium for a significant amount of time after deposition and might be important to consider in evaluating immediate and long-term biological responses to environmental aerosols. Because a $PM_{2.5}$ sampler does not account for all particles with the potential for deposition in the thoracic region, especially for mouth breathers, these model results suggest that ambient air quality regulations should retain a PM_{10} standard.

Breathing mode and ventilatory activity pattern are key parameters that determine initial deposition. Data on differences in ventilatory activity pattern due to age, gender, and disease status would probably provide critical information on variability in susceptibility of the population due to the influence of these factors on dosimetry. Further, to construct total personal exposures, ventilatory activity patterns corresponding to the microenvironments (e.g., activities outdoors versus indoors) for which particles are sampled would be ideal data to facilitate the use of dosimetry models. The dissolution–absorption characteristics of an environmental aerosol are important parameters necessary for improved estimates of cumulative lung burdens of retained particles resulting from chronic inhalation exposures. This information is currently unavailable and is a requirement for making accurate long-term model projections.

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